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Chemistry and environmental significance of aerosols collected in the eastern Tianshan

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ABSTRACT

Aerosol samples were collected at altitudes from 584 m a.s.l. to 3,804 m a.s.l. at seven sites of the eastern Tianshan. The occurrence, distribution, and possible sources of 47 trace metals—including alkali metals and alkali earth metals, transition metals, lanthanoids, and heavy metals—were investigated. It was found that four sampling sites (Shuinichang, 1,691 m a.s.l.; Urumqi City, 809 m a.s.l.; FuKang Station, 584 m a.s.l.; and Bogeda Glacier No. 4, 3,613 m a.s.l.) were contaminated mainly by heavy metals. Other three high-altitude sites (Urumqi Glacier No. 1, 3,804 m a.s.l.; WangFeng road-maintenance station, 3,039 m a.s.l.; and Tianshan Glaciology Station, 2,135 m a.s.l.) were not polluted. The aerosol particles were clustered into two dominant types: crust-originated particles and pollution-derived particles. Aerosols from UG1, WF, and TGS were characterized by crust-originated particles such as clay, plagioclase, dolomite, alkali feldspar, and biotite; while those from SNC, Urumqi, FK, and BG4 were characterized by high content of Cl-rich particles, S-rich particles, and soot. The backward-trajectories results indicated that air masses arriving at SNC, Urumqi, FK, and BG4 were identified as the more polluted source, when compared to the short-range air mass transport from the North to UGI and WF. Relatively lower altitude, as well as terrain blocking, might be another important reason for the gradient difference in pollution influence among these seven places in the Urumqi River Basin.

Keywords: heavy-metal pollution; aerosols; central Asia

1 Introduction

Atmospheric pollution in China, especially in metropolises, has become significantly heavier during the past three decades, with the rapid economic development of industrialization and urbanization (Tan *et al.*, 2013). A great deal of atmospheric pollution research has focused on the middle and eastern parts of China (Lu *et al.*, 2008, 2013; Xiao *et al.*, 2013; Huang *et al.*, 2014; Jiang *et al.*, 2014; Shen *et al.*, 2014; Wei *et al.*, 2014; Yin *et al.*, 2014; Zhang *et al.*, 2016), while the mountain regions in western China have received little attention because of their geographical remoteness (Sexton *et al.*, 1984; Borbon *et al.*, 2002; Guo *et al.*, 2002; Guo *et al.*, 2003; Marker Marker China have received has a statement of the statement o

al., 2004; Li *et al.*, 2014). However, studies have shown that long-range transport of surface emissions and dust storms originating from central Asia could be lifted up into the free troposphere and transported eastward on a hemispheric scale, impacting eastern China, North Korea and South Korea, Japan, and also the United States (Fang *et al.*, 1999; Jaffe *et al.*, 1999; Zhang *et al.*, 2006; Han *et al.*, 2008; Zhang *et al.*, 2009). Regional air pollution study of mountains in western China, therefore, will be a necessary supplement to existing global atmosphere-quality research.

Aerosols collected from Tianshan regions provided an opportunity to study the influence of anthropogenic pollution on this remote area, a topic that has been debated over the past two decades. The Tianshan ranges, located at the center of the arid and semi-arid regions of central Asia, extend over Xinjiang in China, Kirghizstan, and Kazakhstan, for a total length of 2,500 km, and contain many of the world's inland glaciers. Terrestrial dust has been believed by Belikova et al. (1984), Wake et al. (1990), Williams et al. (1992), Sun et al. (1998), Kreutz et al. (2001), Lee et al. (2003), Olivier et al. (2003), and Zhao et al. (2011) to be the main source of the major ions in Tianshan mountain glaciers, suggesting that anthropogenic pollution from surrounding cities and industrial areas has seriously enhanced the concentration of chemical species in this area. Obviously, the diametrically opposed results were due to sampling sites that were upwind or downwind of anthropogenic pollution sources. However, no data has been reported so far based on multi-points gradient sampling including both upwind and downwind sites in this mountain region to reflect the air quality exhaustively; and using only some common chemical elements found in snow or aerosols to deduce the anthropogenic pollution extent is definitely insufficient.

In this research, aerosol field sampling at seven places in the Urumqi River and Sigong River basins was conducted for the first time along an altitude gradient over the eastern Tianshan, with elevations from 584 m to 3,804 m above sea level. In total, 47 trace elements were analyzed to gain comprehensive insight into the long-distance transport of aerosols in the free troposphere and the distribution, as well as the evolution, of anthropogenic pollutions along an altitude gradient in mountainous areas—pollution that has potentially significant impacts on regional and global climate.

2 Experimental

2.1 Sampling site characteristics

Seven sampling sites (Figure 1) were selected in

the Urumqi River and the Sigong River basins, where the weather is controlled by the Mongolian high-pressure system all the year around, with the westerly jet stream prevailing across the mountainous areas. The sampling sites were Urumqi Glacier No. 1 (UG1), the WangFeng road-maintenance station (WF), the Tianshan Glaciology Station (TGS), Shuinichang (SNC), Urumqi City (Urumqi), the FuKang Station (FK), and Bogeda Glacier No. 4 (BG4). Five sites (UG1, WF, TGS, SNC, and BG4) are located in mountains and valleys, while Urumgi and FK are located in urban areas. Glacier BG4 was a typical site downwind of FK, according to the westerly jet stream. These seven sites could represent the different anthropogenic influences throughout the Urumqi River and Sigong River basins in the Tianshan. Details of the sampling sites are described below (Table 1).

Aerosol samples were recovered on Zefluor filters (2.0-µm pore size, 47 mm, Pall Life Sciences) using a 12-V diaphragm pump powered by solar cells, thereby avoiding any contamination from a power generator. Filters were loaded in the field and mounted face down about 2.5 m above the ground surface. The sampling period for each aerosol sample was 4 h. The air volume was converted into standard conditions according to the local ambient conditions. After the sampling period, the filters were removed from the filter holder and placed into clean, airtight plastic containers and stored at 4 °C until analysis. All samples were collected in the autumn of 2012, within a period of just a few days, meaning that possible seasonal influence can be ignored; therefore, we would like to consider the seven sampling sites' element concentration together in the discussion.

2.2 Chemical analysis

The collected aerosol filters were placed in a high-pressure Teflon vessel for digestion, using 2 mL of mixed solution (1.5 mL concentrated HNO₃ and 0.5 mL step). Subsequently, the samples were digested in an oven for 4 h at 190 °C. The solution was heated to 150 °C after cooling, another 0.5 mL HNO₃ was added to the residue, and the sample was further heated on a hot plate at 170 °C for 4 h. This procedure for digestion was repeated twice. In each digestion batch (27 samples), a reagent blank was also used to check the sample-handing processes. A total of 68 elements were measured by Inductively Coupled Plasma-Mass Spectrometry (ICP-SFMS, Element, Bremen, Germany) in a 1,000-class clean room at the State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute (Northwest Institute of Eco-Environment and Resources), Chinese Academy of Sciences.

Elemental concentrations were quantified using

external calibration standards (AccuTrace Reference Standard). A check standard was analyzed after the initial calibration and after every 10 samples. The method's detection limits were listed as follow in Table 2. For precision, the corresponding RSD values of all element concentrations measured in the reference material were less than 5%. The final concentrations were corrected with reagent and filter blanks.



Figure 1 Map showing the location of the sampling sites and the surrounding geographic environment (The sampling sites' details are shown in Figure 6)

	Tal	ble 1 Details of the samp	ling sites	
Sampling sites	Longitude and latitude	Altitude (m a.s.l.)	Character	Sampling time
UG1	43.11°N, 86.81°E	3,804	Valley glacier	Aug. 12
WF	43.11°N, 86.94°E	3,039	Road maintenance station	Aug. 12
TGS	43.21°N, 87.10°E	2,135	Field stations	Aug. 12
SNC	43.45°N, 87.25°E	1,691	Cement factory	Aug. 12
Urumqi	43.85°N, 87.61°E	809	Capital city	Aug. 12
FK	44.15°N, 88.07°E	584	Local city	Aug. 12
BG4	43.83°N, 88.28°E	3,613	Valley glacier	Sep. 12

Individual particles were analyzed using a Field Emission Scanning Electron Microscope (JSM-6701F) equipped with an energy-dispersive X-ray spectrometer (EDX/EDS). A section of each filter was cut and mounted onto the electron microprobe stub and coated with a thin gold film for a higher-quality, secondary electron image. Operating conditions were the following: accelerating voltage = $5 \sim 10 \text{ kV}$; spectral acquisition times = 60 s.

3 Results

3.1 General characteristics of trace elements

Table 2 describes the average concentrations $(\mu g/m^3)$ of the 47 selected elements at the seven sampling sites during the observation period. The daily average concentrations of the 47 selected elements ranged widely, from 0.0003 to 24.447 $\mu g/m^3$.

Based on the standard periodic table and relevant chemical properties, the elements analyzed can be grouped into four categories (Figure 2): (1) alkali metals and alkali earth metals: Na, K, Rb, Be, Mg, Ca, Sr, Ba, and Al; (2) transition metals: Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and Zn; (3) lanthanoids: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu; and (4) heavy elements: As, Sb, Se, Ag, Cd, Hg, Sn, Pb, Tl, Zr, Hf, Ta, W, Th, and U.

Alkali metals and alkali earth metals. The alkali metals and alkali earth metals showed higher concentrations than the other categories. This category showed up as 4 to 155 times higher in Urumqi and FK, as compared to UG1, WF, TGS, SNC, and BG4 (Figure 2).

Transition metals. The transition metals accounted for about 9.2% of the total concentration. Transition metals showed up as 15 to 443 times higher in Urumqi and FK, as compared to UG1, WF, TGS, SNC, and BG4 (Figure 2). Among the transition metals, the Fe content was found to be the highest at these seven sampling sites, with an average concentration of $3.577 \mu g/m^3$.

Lanthanoids. The lanthanoids were found to be the lowest in concentration in the air mass. Lanthanoids at TGS showed up as 3 to 13 times higher, as compared to UG1, WF, SNC, Urumqi, FK, and BG4 (Figure 2).

		Table 2 Co.	ncentrations	of the blanks and the 4	17 selected elements	(µg/m ³) ir	ı aerosol s	amples				
Elements	Detection limit	Blank		Average $(\times 103 \text{ m}/\sigma)$	A viarada (110/m3)	1101	WF	TGS	SNC	Ilmai	ΕV	15d
LIGHICHLS	(bg/g)	Concentration (pg/g)	RSD (%)	- Avelage (~10° þg/g)	Average (µg/III-)	IDO	1	601	ONIC	Ipilipiu	2	PQ4
Alk	ali metals and alka	li earth metals										
Na	3.0	11.78	1.2	2,816.5981	3.8264	0.1475	0.0860	0.7568	0.5789	7.4148	17.6365	0.1645
K	70.6	85.12	0.8	2,303.2847	3.1099	0.0234	0.2476	0.5790	0.2197	7.0436	13.4983	0.1575
Rb	0.4	<d.l.< td=""><td>3.8</td><td>27.4124</td><td>0.0310</td><td>I</td><td>0.0065</td><td>Ι</td><td>I</td><td>0.0737</td><td>0.0556</td><td>0.0814</td></d.l.<>	3.8	27.4124	0.0310	I	0.0065	Ι	I	0.0737	0.0556	0.0814
Be	0.3	0.66	1.9	0.2762	0.0004	0.0001	I	0.0005	0.0004	0.0008	0.0008	0.0001
Mg	10.0	<d.l.< td=""><td>4.0</td><td>2,522.8317</td><td>3.4081</td><td>0.3076</td><td>0.0442</td><td>1.4125</td><td>1.0102</td><td>8.0662</td><td>12.9107</td><td>0.1053</td></d.l.<>	4.0	2,522.8317	3.4081	0.3076	0.0442	1.4125	1.0102	8.0662	12.9107	0.1053
Са	50.7	<d.l.< td=""><td>2.7</td><td>18,113.2404</td><td>24.4470</td><td>0.3134</td><td>0.2757</td><td>23.6882</td><td>4.4946</td><td>69.4026</td><td>71.8072</td><td>1.1476</td></d.l.<>	2.7	18,113.2404	24.4470	0.3134	0.2757	23.6882	4.4946	69.4026	71.8072	1.1476
Sr	0.7	0.80	4.6	88.3915	0.1203	0.0011	0.0011	0.1456	0.0488	0.2713	0.3688	0.0053
Ba	0.5	0.68	2.5	74.5638	0.1007	0.0062	0.0009	0.0305	0.0342	0.2982	0.3324	0.0023
AI	115.2	<d.l.< td=""><td>2.3</td><td>3,549.4434</td><td>4.6979</td><td>0.2656</td><td>0.0798</td><td>1.3837</td><td>0.9370</td><td>16.3207</td><td>12.8952</td><td>1.0035</td></d.l.<>	2.3	3,549.4434	4.6979	0.2656	0.0798	1.3837	0.9370	16.3207	12.8952	1.0035
Transition	metals											
Sc	0.4	0.61	3.5	1.1707	0.0014	0.0002	0.0016	Ι	I	0.0037	0.0046	I
Ti	1.7	2.23	2.3	122.3372	0.1651	I	0.0035	0.0096	I	0.5444	0.5980	I
Λ	0.4	<d.l.< td=""><td>3.3</td><td>4.2089</td><td>0.0057</td><td>I</td><td>I</td><td>0.0097</td><td>0.0029</td><td>0.0154</td><td>0.0122</td><td>I</td></d.l.<>	3.3	4.2089	0.0057	I	I	0.0097	0.0029	0.0154	0.0122	I
Cr	0.6	<d.l.< td=""><td>4.9</td><td>6.6542</td><td>0.0088</td><td>0.0027</td><td>0.0001</td><td>0.0037</td><td>0.0009</td><td>0.0256</td><td>0.0283</td><td>I</td></d.l.<>	4.9	6.6542	0.0088	0.0027	0.0001	0.0037	0.0009	0.0256	0.0283	I
Mn	0.3	0.96	3.1	101.2766	0.1368	0.0014	0.0032	0.0339	0.0073	0.3904	0.5174	0.0040
Fe	66.5	<d.l.< td=""><td>4.8</td><td>2,638.7654</td><td>3.5767</td><td>0.0759</td><td>0.0139</td><td>0.8333</td><td>0.3490</td><td>10.0164</td><td>13.7418</td><td>0.0062</td></d.l.<>	4.8	2,638.7654	3.5767	0.0759	0.0139	0.8333	0.3490	10.0164	13.7418	0.0062
Co	0.2	3.41	3.2	3.8224	0.0053	I	I	0.0024	0.0162	I	0.0144	0.0039
Ni	1.1	3.77	2.1	82.1065	0.1115	Ι	I	0.0205	0.2880	0.1852	0.2182	0.0687
Cu	3.1	3.57	0.9	33.1532	0.0449	0.0022	0.0040	0.0085	0.0131	0.0810	0.2040	0.0016
Zn	7.6	15.99	1.6	418.2211	0.5691	0.0178	0.0020	0.0856	0.0432	1.1412	2.6773	0.0169
D.L. is the	detection limit.											

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Ē		Blank		Average	Average		11M	C C H			Ĩ	
Elements	Detection limit (pg/g)	Concentration (pg/g)	RSD (%)	$(\times 10^3 \text{ pg/g})$	$(\mu g/m^3)$	100	ΚĿ	5	SNC	Urumqi	ΓK	BG4
	Lanthanoids											
La	0.5	0.79	3.2	5.5127	0.0070	0.0027	0.0033	0.0133	0.0024	0.0159	0.0113	0.0000
Ce	0.6	0.80	1.1	17.7898	0.0221	0.0105	0.0117	0.0747	0.0080	0.0143	0.0289	0.0065
Pr	0.4	<d.l.< td=""><td>3.0</td><td>0.7333</td><td>0.0008</td><td>I</td><td>0.0015</td><td>I</td><td>I</td><td>0.0040</td><td>I</td><td>0.0003</td></d.l.<>	3.0	0.7333	0.0008	I	0.0015	I	I	0.0040	I	0.0003
Nd	0.4	<d.l.< td=""><td>1.3</td><td>18.7729</td><td>0.0244</td><td>0.0149</td><td>0.0024</td><td>0.1000</td><td>0.0481</td><td>I</td><td>Ι</td><td>0.0057</td></d.l.<>	1.3	18.7729	0.0244	0.0149	0.0024	0.1000	0.0481	I	Ι	0.0057
Eu	0.1	<d.l.< td=""><td>2.6</td><td>0.5952</td><td>0.0008</td><td>0.0003</td><td>I</td><td>0.0023</td><td>0.0006</td><td>0.0011</td><td>0.0013</td><td>I</td></d.l.<>	2.6	0.5952	0.0008	0.0003	I	0.0023	0.0006	0.0011	0.0013	I
Gd	0.8	<d.l.< td=""><td>1.1</td><td>1.7950</td><td>0.0024</td><td>I</td><td>I</td><td>0.0078</td><td>0.0023</td><td>0.0035</td><td>0.0031</td><td>0.0004</td></d.l.<>	1.1	1.7950	0.0024	I	I	0.0078	0.0023	0.0035	0.0031	0.0004
Tb	0.0	0.23	2.7	1.9057	0.0027	0.0004	I	0.0103	0.0053	I	0.0026	I
Dy	0.4	<d.l.< td=""><td>2.8</td><td>0.8727</td><td>0.0012</td><td>I</td><td>I</td><td>0.0078</td><td>0.0006</td><td>I</td><td>I</td><td>I</td></d.l.<>	2.8	0.8727	0.0012	I	I	0.0078	0.0006	I	I	I
Но	0.1	0.25	3.1	0.3646	0.0005	0.0007	0.0001	I	0.0026	I	I	0.0000
Er	0.3	0.98	1.4	1.4632	0.0019	I	0.0006	0.0079	I	0.0013	0.0038	I
Tm	0.1	0.24	4.0	1.1010	0.0014	0.0001	I	0.0043	0.0006	0.0028	0.0015	0.0007
γb	0.2	<d.l.< td=""><td>2.6</td><td>0.4191</td><td>0.0005</td><td>0.0005</td><td>0.0001</td><td>0.0002</td><td>0.0001</td><td>0.0013</td><td>0.0007</td><td>0.0004</td></d.l.<>	2.6	0.4191	0.0005	0.0005	0.0001	0.0002	0.0001	0.0013	0.0007	0.0004
Lu	1.6	<d.l.< td=""><td>1.9</td><td>0.2796</td><td>0.0003</td><td>0.0002</td><td>0.0000</td><td>I</td><td>I</td><td>I</td><td>I</td><td>0.0016</td></d.l.<>	1.9	0.2796	0.0003	0.0002	0.0000	I	I	I	I	0.0016
Heavy ϵ	slements											
\mathbf{As}	0.3	6.30	4.8	171.3124	0.2334	Ι	0.0003	0.0006	0.1755	0.6679	0.7690	0.0204
\mathbf{Sb}	0.6	<d.l.< td=""><td>3.3</td><td>134.6247</td><td>0.1818</td><td>0.0001</td><td>0.0000</td><td>0.0000</td><td>Ι</td><td>0.6171</td><td>0.6555</td><td>0.0001</td></d.l.<>	3.3	134.6247	0.1818	0.0001	0.0000	0.0000	Ι	0.6171	0.6555	0.0001
Se	0.7	9.81	1.7	125.5035	0.1716	0.0000	0.0000	0.0000	0.0083	0.3586	0.8337	0.0003
Ag	2.0	<d.l.< td=""><td>3.5</td><td>0.4069</td><td>0.0006</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0002</td><td>Ι</td><td>0.0034</td><td>0.0002</td></d.l.<>	3.5	0.4069	0.0006	0.0000	0.0000	0.0000	0.0002	Ι	0.0034	0.0002
Cd	0.2	2.32	4.1	33.7013	0.0424	0.0234	0.0033	0.0348	0.0130	Ι	0.1936	0.0285
Hg	16.0	<d.l.< td=""><td>1.8</td><td>12.9073</td><td>0.0175</td><td>0.0000</td><td>0.0000</td><td>0.0000</td><td>0.0024</td><td>0.0467</td><td>0.0727</td><td>0.0008</td></d.l.<>	1.8	12.9073	0.0175	0.0000	0.0000	0.0000	0.0024	0.0467	0.0727	0.0008
Sn	0.5	2.46	2.4	96.4907	0.1348	0.0000	I	0.0004	0.1264	I	0.7991	0.0175
Pb	0.2	3.57	1.1	230.1054	0.3186	0.0061	I	I	0.5547	0.6024	1.0203	0.0463
II	0.2	6.02	4.6	279.7526	0.3709	0.0000	0.0000	0.0003	0.0209	2.0435	0.5242	0.0071
Zr	0.3	<d.l.< td=""><td>2.6</td><td>2.8075</td><td>0.0037</td><td>I</td><td>0.0005</td><td>0.0013</td><td>0.0009</td><td>0.0124</td><td>0.0094</td><td>0.0011</td></d.l.<>	2.6	2.8075	0.0037	I	0.0005	0.0013	0.0009	0.0124	0.0094	0.0011
Ηf	0.8	<d.l.< td=""><td>3.1</td><td>32.6377</td><td>0.0392</td><td>0.0012</td><td>I</td><td>I</td><td>0.1592</td><td>I</td><td>I</td><td>0.1141</td></d.l.<>	3.1	32.6377	0.0392	0.0012	I	I	0.1592	I	I	0.1141
Та	0.5	7.93	3.9	6.2378	0.0084	0.0002	0.0000	0.0003	0.0011	0.0108	0.0433	0.0029
M	5.0	8.59	2.7	12.2750	0.0167	Ι	0.0000	0.0004	0.0284	0.0880	I	I
Th	0.4	2.63	3.2	2.6113	0.0033	0.0018	I	0.0034	0.0097	Ι	0.0047	0.0037
U	0.3	<d.l.< td=""><td>3.9</td><td>28.0684</td><td>0.0359</td><td>Ι</td><td>0.0000</td><td>Ι</td><td>Ι</td><td>0.0688</td><td>0.1484</td><td>0.0344</td></d.l.<>	3.9	28.0684	0.0359	Ι	0.0000	Ι	Ι	0.0688	0.1484	0.0344
D.L. is th	he detection limit.											

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Figure 2 Four categories of the aerosol elements at seven sampling sites

Heavy elements. The heavy metals accounted for about 2.1% of the total concentration. When the seven different sites were compared, heavy metals showed up as 5 to 1,013 times higher in Urumqi and FK, as compared to UG1, WF, TGS, SNC, and BG4 (Figure 2). Tl and Pb were found to be the high-concentration elements for the transition metals at these seven sampling sites, with average concentrations of 0.371 and 0.319 μ g/m³, respectively.

Overall, the average concentrations of alkali metals, alkali earth metals, and geogenic elements (*e.g.*, Fe) were two to three orders of magnitude higher than those for the transition metals, heavy elements, and lanthanoids.

3.2 Morphology results

The final dataset included around 2,000 particles analyzed on seven filters. The particles were grouped into five dominant types according to their morphology and EDX signal: clay particles (Al₄[Si₄O₁₀], Al₄SiO₂, and Ba[Al₂Si₂O₈]), plagio-clase particles (Na[AlSi₃O₈] and Ca[Al₂Si₂O₈]), dolomite (CaMg[CO₃]₂), alkali feldspar particles (KAlSi₃O₈ - NaAlSi₃O₈), and soot.

4 Discussion

4.1 Enrichment-factor analysis

Trace elements in the atmosphere originate from natural sources such as rock and soil dust, sea-salt spray, volcanoes, wild forest fires, and marine biogenic sources (Lee et al., 2008). On a global scale, however, the emissions of trace elements into the atmosphere from various anthropogenic sources are known to exceed those from natural sources (Nriagu et al., 1989). Crustal enrichment factors (EFc) are often calculated to identify source regions and evaluate the degree of anthropogenic influence (Duce *et al.*, 1975; Cong et al., 2007; Lee et al., 2008; Öztürk et al., 2012). EFc is defined as the concentration ratio of a given element to that of Al (Al, Si, Ti, or Fe were commonly used as approximations of rock and soil dust because they are abundant in crustal material and are not significantly affected by contamination), normalized to the same concentration ratio characteristic of the upper continental crust. For example, the EFc for Cr is thus

$$EFc = \frac{\left(\frac{Cr}{AI}\right)_{aerosol}}{\left(\frac{Cr}{AI}\right)_{crust}}$$
(1)

where Cr represents the element of interest; and Al is a reference element. Here, we have used the data given by Wedepohl (1995) for the upper continental crust. The aerosol and crust subscripts refer to elements in the aerosol samples and crustal material, respectively. An EFc value close to unity is considered as indicating a dominant input from rock and soil, while an EFc value greater than 10 suggests that the corresponding element originated mainly from other sources (Ferrari *et al.*, 2001; Cong *et al.*, 2007; Wu *et al.*, 2009). Figure 4 shows the mean values of crustal enrichment factors for the measured trace elements. The average EFc values are observed to be highly variable between elements, with the lowest value determined for Ti (0.17) and the highest for Se (4,075.49). This wide range of EFc values for the elements is an indicator of the differences in crustal contributions from one group to another.

Overall, the mean values of EFc are relatively lower for the 47 selected trace elements (including alkali metals, alkali earth metals, transition metals, lanthanoids, and heavy metals) in UG1, WF, and TGS, as compared to Urumqi, FK, and BG4 (Figure 2). The distinct differences are detailed below.

Alkali metals, alkali earth metals, and former transition metals showed low EFc values (all less than 10, except for Rb valued at 12.47) for all of the seven sites (Figure 2), indicating their crustal origins. The lanthanoids have average EFc values of 10 < EFc < 100, and thus are considered moderately enriched, with the following order of occurrence: Yb (10.37) < Gd (10.61) < La (11.57) < Eu (14.00) < Pr (15.59) < Ce (23.07) < Er (32.25) < Lu (38.18) < Ho (40.56) < Nd (42.30) < Tm (78.16) < Tb (98.60).

Previous studies showed that when enrichment factors of lanthanoids in atmospheric particles are between 3 and 10, it indicates the influence of anthropogenic pollution in the atmosphere on these elements, while values between 1 and 3 indicate their main source is dust from the ground (Wang *et al.*, 2008).

In our study, the lanthanoids showed high EFc values (all higher than 10) at all of the seven sites (Figure 2), indicating the possibility of anthropogenic influence.

Heavy elements were found to be highly enriched, with EFc values greater than 100, ranging from 198 to 4,075 at all seven aerosol-sample sites. The order of occurrence was U (198.11) < Pb (264.29) < W (307.35) < Hf (326.43) < As (663.46) < Sn (781.94) < Tl (1,331.63) < Hg (1,526.21) < Sb (2,525.16) < Se (4,075.49).

When the seven different sites were compared, higher average EFc values of lanthanoids showed up at UG1, WF, and TGS, as compared to Urumqi, FK, and BG4 (Figure 5). Conversely, higher average EFc values of heavy metals showed up at Urumqi, FK, and BG4, as compared to UG1, WF, and TGS. The SNC sample was highly enriched with both lanthanoids and heavy metals (Figure 5). The altitude order is UG1 (3,804 m a.s.l.), WF (3,039 m a.s.l.), TGS (2,135 m a.s.l.), SNC (1,691 m a.s.l.), Urumqi (809 m a.s.l.), FK (584 m a.s.l.), and BG4 (3,613 m a.s.l.) (Figure 1). According to this interesting characteristic of EFc values—combined with altitudes of the seven sites—local meteorology (such as wind stress and direction), as

well as air mass trajectories, must be considered as an important contributor to the explanation, as discussed below.

For example, although UG1 and BG4 are both high-altitude glaciers, the lanthanide enrichment is much higher at UG1 than at BG4. The local wind condition should be the main reason. The State Road No. 216 is sited 2 km southeast of UG1. This road crossing the mountains and the glaciers in this area is made of sands and clay. The dust and vehicle emissions caused by passing cars had been very easily carried to UG1 by the southeasterly mountain valley wind, which is the frequent wind direction during the daytime. That is why the influence of the local wind cannot be ignored.

4.2 Individual particle analysis

Figure 2 shows at different magnifications typical individual particles from the Urumqi River Basin, loaded on the filters.

According to the results of the enrichment-factors analysis above, two particle categories could be obtained, based on the morphology and chemical characteristics of the individual particles. The distinct characteristics and possible origins of each group are described in detail as follows.

Crust-originated particles: clay; plagioclase; dolomite, CaMg(CO₃)₂; and alkali feldspar, KAlSi₃O₈ - NaAlSi₃O₈. Clay particles were rich at WF. The clay particles are characterized by high content of Si and Al, with varying Mg/Ca. At UG1, plagioclase particles were rich, consisting of high content of Na[AlSi₃O₈] and Ca[Al₂Si₂O₈]. From the point of view of mineralogy, clay particles usually include Al₄[Si₄O₁₀], Al₄SiO₂, Ca[Al₂Si₂O₈], and Ba[Al₂Si₂O₈], which are typical terrigenous minerals. Feldspar (KAlSi₃O₈ - NaAlSi₃O₈) turns into clay under the weathering process (Cong *et al.*, 2010a). Therefore, a large fraction of the irregularly shaped particles (Figure 3a) identified as alumosilicates could be attributed to eolian dispersion of soil particles.

Besides, few particles consisting predominantly of Si and Fe were detected in aerosol samples from UG1, WF, and TGS. The Si/Fe-rich particles are considered to be biotite (K(Mg, Fe)₃[AlSi₃O₁₀(OH, F)₂]), as biotite (generally associated with magnetite) is abundant in West China, especially in the Xinjiang Uygur Autonomous Region. Besides soil dispersion, Fe-rich particles could also be produced by coal-fired boilers and metal industry (Zhao *et al.*, 2011). Fe-rich particles emanating from a high-temperature furnace usually show a spherical shape (Cong *et al.*, 2010b). However, all of the Si/Fe-rich particles in this study have irregular (nonspherical) morphology (Figure 3b) and thus can be identified as of natural origin.



Figure 3 SEM images of typical aerosol particles. (a, b) crust-originated particles; (c) pollution-derived particles; (d, e, f) particles containing soot, with varying heavy metals and crustal elements



Figure 4 Enrichment factors (EFc) of aerosols, relative to the reference element Al

Pollution-derived particles: Important sources of atmospheric lead include emissions from automobile exhaust, coal combustion, mining or smelting operations, and waste incineration. Aerosol samples collected at SNC, Urumqi, and FK were characterized by high content of Cl-rich particles, S-rich particles, and soot; and containing only a small amount of Na, Ti, and Pb (Figure 3c). It has been verified that airborne Pb can be carried globally through long-range transport, as it tends to concentrate on fine particles that have a long residence time in the atmosphere (Cong *et al.*, 2010a). Furthermore, Rattigan *et al.* (2001) suggested that approximately 70% of aerosol Pb could be ascribed to leaded gasoline. As analyzed above, Pb showed high absolute EFc values of 1,409.06, 87.85, 188.32, and 109.81 at SNC, Urumqi, FK, and BG4, respectively, indicating the serious impact of anthropogenic activities.



Figure 5 Enrichment factors (EFc) variations of lanthanoids and heavy metals at the seven sampling sites

Soot could be clearly distinguishable from other aerosol types due to its unique morphology, as shown in Figure 3d. The morphology of this kind of particle varies from short chains to complex clusters, depending on the type of fuel, burning conditions, and atmospheric processing (Chakrabarty et al., 2006; Yue et al., 2006). In our study, a considerable percentage of soot particles contained S, Cr, Zn, Pb, and Ni, with varying crustal elements (e.g., Al, K, and Ca), which were observed by EDX analysis, indicating a mixed source for these particles. Paoletti et al. (2003) suggested that the S content in soot aggregates was probably caused by a gas-to-particle conversion process during transport (Pósfai et al., 2003). Other unrecognized particles could contain organic particles with light elements (such as C, N, and O) or biological particles.

4.3 Possible source investigation

To investigate potential source regions of pollution-derived heavy metals in aerosols from these seven sampling sites, 5-day backward trajectories were computed using the hybrid single-particle Lagrangian integrated trajectory (HYSPLIT-4) model developed by the National Oceanic and Atmospheric Administration (http://www.arl.noaa.gov/ready/hysplit4.html). The trajectories were calculated at 500 m above ground level for the seven sampling sites (Figure 6).

In general, the larger part of the air mass arriving at UG1 and WF was from short-range aerosol transport from the north; and the air mass arriving at SNC, Urumqi, FK, and BG4 was from long-range aerosol transport from the west.

(1) The trajectories arriving at UG1 and WF reflected short-range aerosol transport, originating from the south slope of the Altai Mountains at an altitude of 1,117 m a.s.l., down to 311 m a.s.l. along the western edge of the Jungger basin, subsequently climbing up along the north slope of the Tianshan from several hundreds to around one-thousand metres a.s.l., immediately across the valley straight to the south until blocked by high mountains with an altitude of 2,702 m a.s.l., then flowing into the low places and turning to the southeast, finally arriving at UG1 and WF. It is clear that samples from these air masses exhibited higher average EFc values of lanthanoids and lower values of heavy metals at UG1, WF, and TGS, as compared to Urumqi, FK, and BG4, indicating less pollutant was carried by their trajectories.

(2) The trajectories arriving at SNC, Urumqi, FK, and BG4 reflected long-range aerosol transport, originating from the northwestem regions near Siberia and passing through east Kazakhstan, the Karamay oilfield, the Gurbantunggut Desert, and the south edge of the Jungger Basin. Samples from these four sites, where the northerly air mass arrived, exhibited high EFc values of pollution-derived heavy metals (U, Pb, W, Hf, As, Sn, Tl, Hg, Sb, and Se) (Figure 4). Especially, it is to be noted that these air masses traveled across the Semipalatinsk Test Site (Figures 1 and 6).

The Semipalatinsk Nuclear Test Site (SNTS) (50°07'N, 78°43'E) was the primary testing venue for the Soviet Union's nuclear weapons for more than 40 years (Olivier *et al.*, 2003; Semiochkina *et al.*, 2004; Zhang *et al.*, 2011). It is located in northeast Kazakhstan, in the south valley of the Irtysh River. The nuclear test site was located around 150 km west of the town of Semipalatinsk, near the border of the East Kazakhstan Province and Pavlodar Province, with most of the nuclear tests taking place at various sites farther to the west and the south, some as far away as Karagandy Province (Zhang *et al.*, 2011). The current and future risk to people living in the contaminated

area has been evaluated by Semiochkina *et al.* (2004) using Internal doses; results indicated that wholebody measurements calculated for adults are in the range of 13 to 500 μ Sv/y even nowadays (Semiochkina *et al.*, 2004). Recent studies also pointed out pollution levels of heavy metals such as Pb, Cd still exceed the national limit in the Semipalatinsk Nuclear Test Site (SNTS) region of East Kazakhstan.



Figure 6 Daily backward trajectories terminating at the sampling site

According to data derived from backward air trajectories from the Tianshan, the typical transit time from possible major source regions is 0.5 to 1 day in the summer. Our sampling site is therefore assumed also to be affected by long-range transport of heavy metals (U, Pb, W, Hf, As, Sn, Tl, Hg, Sb, and Se) arriving at SNC, Urumqi, FK, and BG4 via emissions from the Karamay oilfield and nuclear test sites like Semipalatinsk.

(3) Aerosol samples collected at FK showed that the site has been seriously polluted by heavy metals. The advantageous industries of FK City fall to coal production, coal chemical industry, nonferrous metal production, and subsequent deep processing of oil and gas (Wu *et al.*, 2008). FK has roughly 28 coal-related factories, especially those for electrolytic nickel production. In addition, FK produced 3,256 t of electrolytic nickel in 2005, with 3.87 times of the nation's growth rate (Wu *et al.*, 2008). All of these industrial factories cannot shirk responsibility for the heavy metal polluted aerosols at FK. This industrial activity could also be one of the important reasons for BG4 showing higher average heavy-metals EFc values than UG1 (Figure 4), because the trajectories arriving at BG4 pass through FK City.

Besides the factors discussed above, BG4 is a high-altitude site; but it is more polluted (in terms of heavy-metals EFs) when compared with UG1, likely because BG4 is located downwind of the pollution-emission region, FK.

5 Conclusion

Aerosol samples collected along an altitude gradient from 584 m a.s.l to 3,804 m a.s.l at seven sites showed that four of those sampling sites (SNC, Urumqi City, FK, and BG4) were contaminated mainly by heavy metals; and the heavy metals increased rapidly

with the reduction in altitude in both the Urumgi River and Sigong River basins. Aerosols from SNC, Urumqi, FK, and BG4 were characterized by high contents of Cl-rich particles, S-rich particles, and soot. The backward-trajectories results indicated that air masses arriving at SNC, Urumqi, FK, and BG4 were identified as the more polluted source, when compared to UG1 and WF, sites of short-range air mass transport from the north. Low altitude, as well as terrain blocking, might be another important reason for the gradient difference in pollution influence among these seven places in the Urumqi River Basin. Samples from SNC, Urumqi, FK, and BG4 exhibited a high daily percentage of pollution-derived heavy metals, as well as high concentrations of all individual heavy metals, such as Sb, Ag, Se, As, Hg, Ta, Tl, Sn, and Pb.

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References:

- Belikova TV, Vasilenko VN, Nazarov IM, et al., 1984. Characteristics of background sulfate pollution of the snow cover on the territory of the USSR. Meteorologiya i Gidrologiya, 9: 47–55.
- Borbon A, Locoge N, Veillerot M, et al., 2002. Characterisation of NMHCs in a French urban atmosphere: overview of the main sources. Science of the Total Environment, 292(3): 177–191. DOI: 10.1016/S0048-9697(01)01106-8.
- Chakrabarty RK, Moosmuller H, Garro MA, et al., 2006. Emissions from the laboratory combustion of wildland fuels: Particle morphology and size. Journal of Geophysical Research: Atmospheres, 111(D7): D07204. DOI: 10.1029/2005JD006659.
- Cong ZY, Kang SC, Liu XD, et al., 2007. Elemental composition of aerosol in the Nam Co region, Tibetan Plateau, during summer monsoon season. Atmospheric Environment, 41(6): 1180–1187. DOI: 10.1016/j.atmosenv.2006.09.046.
- Cong ZY, Kang SC, Dong SP, et al., 2010a. Elemental and individual particle analysis of atmospheric aerosols from high Himalayas. Environmental Monitoring and Assessment, 160(1–4): 323–335. DOI: 10.1007/s10661-008-0698-3.

Cong ZY, Kang SC, Zhang YL, et al., 2010b. Atmospheric wet depos-

ition of trace elements to central Tibetan Plateau. Applied Geochemistry, 25(9): 1415–1421. DOI: 10.1016/j.apgeochem. 2010.06.011.

- Duce RA, Hoffman GL, Zoller WH, 1975. Atmospheric trace metals at remote northern and southern hemisphere sites: pollution or natural? Science, 187(4171): 59–61. DOI: 10.1126/science.187.4171.59.
- Fang M, Zheng M, Wang F, et al., 1999. The long-range transport of aerosols from northern China to Hong Kong–a multi-technique study. Atmospheric Environment, 33(11): 1803–1817. DOI: 10.1016/S1352-2310(98)00318-5.
- Ferrari CP, Clotteau T, Thompson LG, et al., 2001. Heavy metals in ancient tropical ice: initial results. Atmospheric Environment, 35(33): 5809–5815. DOI: 10.1016/S1352-2310(01)00347-8.
- Guo H, Wang T, Simpson IJ, et al., 2004. Source contributions to ambient VOCs and CO at a rural site in eastern China. Atmospheric Environment, 38(27): 4551–4560. DOI: 10.1016/j.atmosenv. 2004.05.004.
- Han YX, Fang XM, Zhao TL, et al., 2008. Long range trans-Pacific transport and deposition of Asian dust aerosols. Journal of Environmental Sciences, 20(4): 424–428. DOI: 10.1016/S1001-0742(08)62074-4.
- Huang K, Fu JS, Gao Y, *et al.*, 2014. Role of sectoral and multi-pollutant emission control strategies in improving atmospheric visibility in the Yangtze River Delta, China. Environmental Pollution, 184: 426–434. DOI: 10.1016/j.envpol.2013.09.029.
- Jaffe D, Anderson T, Covert D, et al., 1999. Transport of Asian air pollution to North America. Geophysical Research Letters, 26(6): 711–714. DOI: 10.1029/1999GL900100.
- Jiang YL, Zhuang GS, Wang QZ, et al., 2014. Aerosol oxalate and its implication to haze pollution in Shanghai, China. Chinese Science Bulletin, 59(2): 227–238. DOI: 10.1007/s11434-013-0009-4.
- Kreutz KJ, Aizen VB, Cecil LD, et al., 2001. Oxygen isotopic and soluble ionic composition of a shallow firn core, Inilchek glacier, central Tien Shan. Journal of Glaciology, 47(159): 548–554. DOI: 10.3189/172756501781831819.
- Lee K, Hur SD, Hou SG, *et al.*, 2008. Atmospheric pollution for trace elements in the remote high-altitude atmosphere in central Asia as recorded in snow from Mt. Qomolangma (Everest) of the Himalayas. Science of the Total Environment, 404(1): 171–181. DOI: 10.1016/j.scitotenv.2008.06.022.
- Lee XQ, Qin DH, Jiang GB, et al., 2003. Atmospheric pollution of a remote area of Tianshan Mountain: ice core record. Journal of Geophysical Research, 108(D14): 4406. DOI: 10.1029/2002JD002181.
- Li Q, Song JP, Wang ER, et al., 2014. Economic growth and pollutant emissions in China: a spatial econometric analysis. Stochastic Environmental Research and Risk Assessment, 28(2): 429–442. DOI: 10.1007/s00477-013-0762-6.
- Liu PF, Zhao CS, Zhang Q, *et al.*, 2009. Aircraft study of aerosol vertical distributions over Beijing and their optical properties. Tellus B, 61(5): 756–767. DOI: 10.1111/j.1600-0889.2009.00440.x.
- Lu C, Deng QH, Ou CY, et al., 2013. Effects of ambient air pollution on allergic rhinitis among preschool children in Changsha, China. Chinese Science Bulletin, 58(34): 4252–4258. DOI: 10.1007/s11434-013-5725-2.
- Lu H, Zhu LZ, Chen SG, 2008. Pollution level, phase distribution and health risk of polycyclic aromatic hydrocarbons in indoor air at public places of Hangzhou, China. Environmental Pollution, 152(3): 569–575. DOI: 10.1016/j.envpol.2007.07.005.
- Nriagu JO, 1989. A global assessment of natural sources of atmospheric trace metals. Nature, 338(6210): 47–49. DOI: 10.1038/ 338047a0.

- Olivier S, Schwikowski M, Brütsch S, et al., 2003. Glaciochemical investigation of an ice core from Belukha glacier, Siberian Altai. Geophysical Research Letters, 30(19): 2019. DOI: 10.1029/2003GL018290.
- Öztürk F, Zararsız A, Dutkiewicz VA, *et al.*, 2012. Temporal variations and sources of Eastern Mediterranean aerosols based on a 9-year observation. Atmospheric Environment, 61: 463–475. DOI: 10.1016/j.atmosenv.2012.07.051.
- Paoletti L, De Berardis B, Arrizza L, *et al.*, 2003. Seasonal effects on the physico-chemical characteristics of PM_{2.1} in Rome: a study by SEM and XPS. Atmospheric Environment, 37(35): 4869–4879. DOI: 10.1016/j.atmosenv.2003.08.031.
- Pósfai M, Simonics R, Li J, et al., 2003. Individual aerosol particles from biomass burning in southern Africa: 1. Compositions and size distributions of carbonaceous particles. Journal of Geophysical Research: Atmospheres, 108(D13): 8483. DOI: 10.1029/2002JD 002291.
- Rattigan OV, Mirza MI, Ghauri BM, et al., 2001. Aerosol sulfate and trace elements in urban fog at Lahore, Pakistan. Abstr Pap Am Chem S, 222: U475.
- Semiochkina N, Voigt G, Mukusheva M, et al., 2004. Assessment of the current internal dose due to ¹³⁷Cs and ⁹⁰Sr for people living within the Semipalatinsk Test Site, Kazakhstan. Health Physics, 86(3): 187–192.
- Sexton K, Westberg H, 1984. Nonmethane hydrocarbon composition of urban and rural atmospheres. Atmospheric Environment, 18(6): 1125–1132. DOI: 10.1016/0004-6981(84)90144-6.
- Shen GF, Yuan SY, Xie YN, *et al.*, 2014. Ambient levels and temporal variations of PM_{2.5} and PM₁₀ at a residential site in the megacity, Nanjing, in the western Yangtze River Delta, China. Journal of Environmental Science and Health, Part A, 49(2): 171–178. DOI: 10.1080/10934529.2013.838851.
- Sun JY, Qin DH, Mayewski PA, et al., 1998. Soluble species in aerosol and snow and their relationship at Glacier 1, Tien Shan, China. Journal of Geophysical Research: Atmospheres, 103(D21): 28021–28028. DOI: 10.1029/98JD01802.
- Tan HB, Yin Y, Gu XS, et al., 2013. An observational study of the hygroscopic properties of aerosols over the Pearl River Delta region. Atmospheric Environment, 77: 817-826. DOI: 10.1016/j.atmosenv.2013.05.049.
- Wake CP, Mayewski PA, Spencer M, 1990. A review of central Asian glaciochemical data. Annals of Glaciology, 14: 301–306. DOI: 10.1017/S026030550000879X.
- Wang ZW, Zhang XS, Mu YJ, 2008. Effects of rare-earth fertilizers on the emission of nitrous oxide from agricultural soils in China. Atmospheric Environment, 42(16): 3882–3887. DOI: 10.1016/j.atmosenv.2008.01.018.
- Wedepohl KH, 1995. The composition of the continental crust. Geochimica et Cosmochimica Acta, 59(7): 1217–1232. DOI:

10.1016/0016-7037(95)00038-2.

- Wei JC, Guo XM, Marinova D, et al., 2014. Industrial SO₂ pollution and agricultural losses in China: evidence from heavy air polluters. Journal of Cleaner Production, 64: 404–413. DOI: 10.1016/j.jclepro.2013.10.027.
- Williams MA, Tonnessen KA, Melack JM, et al., 1992. Sources and spatial variation of the chemical composition of snow in the Tien Shan, China. Annals of Glaciology, 16: 25–32. DOI: 10.1017/S0260305500004778.
- Wu DW, Yang DG, Mao HY, et al., 2008. Structuring recycle economy of advantageous industries: a case study of Fukang City, Xinjiang. Arid Land Geography, 31(5): 779–787.
- Wu GJ, Xu BQ, Yao TD, et al., 2009. Heavy metals in aerosol samples from the Eastern Pamirs collected 2004–2006. Atmospheric Research, 93(4): 784–792. DOI: 10.1016/j.atmosres.2009.03.011.
- Xiao R, Bai JH, Huang LB, et al., 2013. Distribution and pollution, toxicity and risk assessment of heavy metals in sediments from urban and rural rivers of the Pearl River delta in southern China. Ecotoxicology, 22(10): 1564–1575. DOI: 10.1007/ s10646-013-1142-1.
- Yin WQ, Wang L, Li RR, *et al.*, 2014. Personal exposure levels of PAHs in the general population in northern rural area of Jiangsu Province, China. Journal of Environmental Science and Health, Part A, 49(3): 281–286. DOI: 10.1080/10934529.2014.846604.
- Yue WS, Lia XL, Liu JF, et al., 2006. Characterization of PM_{2.5} in the ambient air of Shanghai city by analyzing individual particles. Science of the Total Environment, 368(2–3): 916–925. DOI: 10.1016/j.scitotenv.2006.03.043.
- Zhang L, Jacob DJ, Boersma KF, et al., 2008. Transpacific transport of ozone pollution and the effect of recent Asian emission increases on air quality in North America: an integrated analysis using satellite, aircraft, ozonesonde, and surface observations. Atmospheric Chemistry and Physics, 8(20): 6117–6136. DOI: 10.5194/ acp-8-6117-2008.
- Zhang Q, Zhao CS, Tie XX, et al., 2006. Characterizations of aerosols over the Beijing region: a case study of aircraft measurements. Atmospheric Environment, 40(24): 4513–4527. DOI: 10.1016/j.atmosenv.2006.04.032.
- Zhang XY, Edwards R, 2011. Anthropogenic sulfate and nitrate signals in snow from bogda glacier, eastern tianshan. Journal of Earth Science, 22(4): 490–502. DOI: 10.1007/s12583-011-0196-3.
- Zhang XY, Li ZQ, Zhou P, et al., 2016. Characteristics and source of aerosols at Shiyi Glacier, Qilian Mountains, China. Sciences in Cold and Arid Regions, 8(2): 135–146. DOI: 10.3724/SP.J.1226. 2016.00135.
- Zhao SH, Li ZQ, Zhou P, 2011. Ion chemistry and individual particle analysis of atmospheric aerosols over Mt. Bogda of eastern Tianshan Mountains, Central Asia. Environmental Monitoring and Assessment, 180(1–4): 409–426. DOI: 10.1007/s10661-010-1796-6.